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SKIN TEMPERATURE RISE IN AN AIRCRAFT
EXPOSED TO THERMAL RADIATION FROM A
NUCLEAR EXPLOSION

UNITED STATES ATOMIC ENERGY COMMISSION

ROYAL AIRCRAFT ESTABLISHMENT

Farnborough, Southampton, England

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SKIN TEMPERATURE RISE IN AN AIRCRAFT EXPOSED TO THERMAL RADIATION FROM A NUCLEAR EXPLOSION

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March 1958

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SKIN TEMPERATURE RISE IN AN AIRCRAFT
EXPOSED TO THERMAL RADIATION
FROM A NUCLEAR EXPLOSION

SUMMARY

It is shown that, in many situations, aerodynamic cooling substantially reduces the temperature rise in thin skins of aircraft exposed in flight to thermal radiation from nuclear explosions. The maximum acceptable thermal dose, where this is determined by skin temperature rise, depends upon the time scale of the thermal input and thus upon the yield of the weapon involved.

The problem is attacked by a finite difference analysis, and the maximum temperature rise and the time at which it occurs are shown to depend on a single non-dimensional parameter. The results are presented for a range of this parameter corresponding to the majority of practical situations.

1   INTRODUCTION

In many situations, the maximum yield of weapon which an aircraft may safely deliver is governed by the thermal dose it can withstand. In particular, the temperature rise in the skin may be limited to some critical value determined by deterioration of the properties of the material or by unacceptably high thermal stresses. It is clear that the operational capabilities of an aircraft can only be determined realistically if both the critical temperature limits and the temperature rise in a given situation are known accurately. This Note considers the latter factor.

In previous British analyses of the effects of thermal radiation on aircraft, it has been assumed that the incident thermal dose, corrected for reflection at the surface and the obliquity of the skin to the direction of propagation, is thereafter totally absorbed by the skin and contributes in its entirety to the temperature rise. It was known that during the time in which the thermal radiation was received, some heat would be lost from the surface by forced convection to the airstream, but this effect had not been evaluated and had been considered to be a factor of safety. With the advent of thermonuclear weapons of high yield, it has now become necessary to examine this and other safety factors, in order to determine whether these weapons can be delivered at all by existing aircraft without damaging them seriously.

This Note considers the effect of aerodynamic cooling on the temperature rise of aircraft skins exposed to thermal radiation from nuclear weapons. The analysis is generalised and the range of variables chosen is believed to cover any likely situation.

2   RATE OF THERMAL INPUT

The thermal energy from a nuclear explosion is released in a pulse, the rate of output rising rapidly to a peak and decaying more slowly over a relatively long period of time.   It is possible to represent the thermal pulse in a generalised form giving the rate of thermal energy release as a fraction of its peak value, in terms of a non-dimensional time whose units are the time t_{max} at which the energy release is a maximum, i.e.

$$P(t)/P_{max} = f(t/t_{max}) . \qquad (1)$$

This function, which is independent of yield, is shown in Fig.1[1]; it also represents the shape of the pulse received by a surface exposed to the radiation.

In the subsequent analysis, the amount of energy received up to a given time is required, and this is obtained from an integral of equation (1) and takes the non-dimensional form

$$Q(t)/Q = f(t/t_{max}) \qquad (2)$$

where Q is the total thermal energy received.   A curve of equation (2), of American origin, has been widely published[1] and is shown in Fig.2.   The data actually used in this study are very similar to those represented in Fig.2, but were obtained in British trials with weapons in the megaton range[2]. There appear to be no data for times longer than 10 t_{max}, and it is of importance to note that only about 80% of the thermal energy is released up to this time.   Since

$$t_{max} = 0.032 \ W^{\frac{1}{2}} \ secs \ (Ref.1) \qquad (3)$$

it may be seen that some 20% of the thermal energy is still to be released after a time $t = 0.32 \ W^{\frac{1}{2}}$, which for a 5 Mt weapon, for example, is 22.6 secs.   The fact that most of the energy is released after the peak permits a significant amount of convective cooling to occur in most circumstances, as shown below.

3   RATE OF HEAT LOSS

It is assumed that the rate of loss of heat from an aircraft skin to the airstream can be represented by a heat transfer coefficient h such that when the temperature difference between the skin and the airstream is T, the rate of heat loss per unit area is hT.   It is not proposed to enter into a detailed examination of means by which the heat transfer coefficient may be calculated in different circumstances, but a brief statement of relevant data is given below.

The heat transfer coefficient at any point depends upon the conditions in the boundary layer and the location of the point.   It is usually

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assumed that the development of the boundary layer is similar to that on a flat plate, for which considerable experimental data are available. A number of empirical formulae have been developed to represent these data, and those recommended for use in kinetic heating studies seem to be the most appropriate[3]. At any point whose distance is x downstream from the leading edge, the local heat transfer coefficient is given by

$$h = 0.332 \, \rho V c_p \, Pr^{-2/3} \, Re^{-1/2} \qquad (4)$$

when the flow in the boundary layer is laminar, and by

$$h = 0.176 \, \rho V c_p \, (\log_{10} Re)^{-2.45} \qquad (5)$$

when the flow in the boundary layer is turbulent. These equations may be modified by compressibility effects and chordwise pressure gradients and the heat transfer coefficient also varies somewhat with the temperature difference T when this becomes large. The effects of some of these factors are considered elsewhere, and appropriate specialist reports should be consulted[3,4,5]. It will be seen later, however, that the maximum temperature rise in many situations is relatively insensitive to the heat transfer coefficient, to an extent which makes great accuracy in determining the latter unnecessary.

4   RATE OF TEMPERATURE RISE

In attempting a general analysis of the rate of increase in skin temperature, it is necessary to make the following assumptions, all of which appear to be justified in the majority of situations:

(a)   The heat transfer coefficient remains constant.

(b)   The thermal properties of the skin material remain constant.

(c)   The reflectivity of the surface remains constant.

(d)   The skin and boundary layer temperatures are initially equal.

(e)   There are no temperature gradients through the skin.

(f)   Heat loss to adjacent structure is negligible.

(g)   Heat loss by radiation is negligible.

Under these circumstances the temperature rise in the skin is governed by the differential equation

$$z c \ell \frac{dT}{dt} = P(t) - hT \qquad (6)$$

where, in this context, $P(t)$ is the rate of heat input per unit area of skin at time t.

Clearly, equation (6) can only be evaluated if $P(t)$ is known as an analytic function of time. Since it is not, it is necessary to consider an

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analysis using finite differences of the variables.　Equation (6) then becomes

$$zc\ell \frac{\Delta T}{\Delta t} = P(t) - hT \qquad (7)$$

or

$$\Delta T = \frac{P(t) \Delta t}{zc\ell} - \frac{hT \Delta t}{zc\ell} \qquad (8)$$

where T is taken as the temperature rise at the centre of the time interval Δt.　Now $P(t)\Delta t$ is the amount of heat entering the skin during the interval Δt, which is $\Delta Q(t)$.　Then

$$\Delta T = \frac{\Delta Q(t)}{zc\ell} - \frac{hT \Delta t}{zc\ell} \quad . \qquad (9)$$

To effect a general solution, we may make the substitutions

$$\Delta Q(t) = \frac{\Delta Q(t)}{Q} \cdot Q$$

and

$$\Delta t = \frac{\Delta t}{t_{max}} \cdot \tau_{max} \quad .$$

Further, let

$$\frac{Q}{zc\ell} = T_i \qquad (10)$$

where T_i is the "ideal" temperature rise which would result if no heat were lost, and let

$$\frac{ht_{max}}{zc\ell} = b \qquad (11)$$

where b is a non-dimensional variable.

Then equation (9) becomes

$$\Delta T = \frac{\Delta Q(t)}{Q} \cdot T_i - b \cdot \frac{\Delta t}{t_{max}} \cdot T \qquad (12)$$

whence

$$\frac{\Delta T}{T_i} = \frac{\Delta Q(t)}{Q} - b \cdot \frac{\Delta t}{t_{max}} \frac{T}{T_i} \qquad (13)$$

a non-dimensional equation.

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Then during the nth interval of time the non-dimensional temperature rise increases by

$$\frac{\Delta T_n}{T_i} = \frac{\Delta Q(t)_n}{Q} - b \cdot \frac{\Delta t}{t_{max}} \cdot \frac{T_n}{T_i} \qquad (14)$$

At the end of this interval, let the non-dimensional temperature rise be $\dfrac{\overline{T_n}}{T_i}$, where

$$\frac{\overline{T_n}}{T_i} = \frac{T_n}{T_i} + \frac{1}{2} \cdot \frac{\Delta T_n}{T_i} \qquad (15)$$

During the next interval, the non-dimensional temperature rise increases by

$$\frac{\Delta T_{n+1}}{T_i} = \frac{\Delta Q(t)_{n+1}}{Q} - b \cdot \frac{\Delta t}{t_{max}} \cdot \frac{T_{n+1}}{T_i} \qquad (16)$$

But

$$\frac{\Delta T_{n+1}}{T_i} = 2 \left\{ \frac{T_{n+1}}{T_i} - \frac{\overline{T_n}}{T_i} \right\} \qquad (17)$$

Then equation (16) gives

$$\frac{T_{n+1}}{T_i} = \left\{ \frac{\overline{T_n}}{T_i} + \frac{1}{2} \cdot \frac{\Delta Q(t)_{n+1}}{Q} \right\} \left(1 + \frac{b}{2} \cdot \frac{\Delta t}{t_{max}} \right)^{-1} \qquad (18)$$

Now the non-dimensional temperature rise at the end of the (n+1)th interval is given by

$$\frac{\overline{T_{n+1}}}{T_i} = \frac{T_{n+1}}{T_i} + \frac{1}{2} \cdot \frac{\Delta T_{n+1}}{T_i} \qquad (19)$$

and substituting for $\dfrac{\Delta T_{n+1}}{T_i}$ from equation (17)

$$\frac{\overline{T_{n+1}}}{T_i} = \frac{2\, T_{n+1}}{T_i} - \frac{\overline{T_n}}{T_i} \qquad (20)$$

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It is now possible to erect a series from which the temperature rise at any time can be determined. During the first interval

$$\frac{\Delta T_1}{T_i} = \frac{2 T_1}{T_i} \qquad (21)$$

and thus, from equation (14)

$$\frac{T_1}{T_i} = \frac{1}{2} \frac{\Delta Q(t)_1}{Q} \cdot \left(1 + \frac{b}{2} \cdot \frac{\Delta t}{t_{max}} \right)^{-1} \qquad (22)$$

and

$$\frac{\overline{T_1}}{T_i} = \frac{2 T_1}{T_i} \qquad (23)$$

Subsequently

$$\frac{T_{n+1}}{T_i} = \left\{ \frac{\overline{T_n}}{T_i} + \frac{1}{2} \frac{\Delta Q(t)_{n+1}}{Q} \right\} \left(1 + \frac{b}{2} \cdot \frac{\Delta t}{t_{max}} \right)^{-1} \qquad (18)$$

and

$$\frac{\overline{T_{n+1}}}{T_i} = \frac{2 T_{n+1}}{T_i} - \frac{\overline{T_n}}{T_i} \, . \qquad (20)$$

Using equations (22), (23), (18) and (20) in turn, the variation of T/T_i with t/t_{max} may be determined for any value of the non-dimensional variable b. Thus the temperature rise time-history for any situation may be presented in terms of one parameter. In using this method, it should be noted that the temperature rise T_n occurs at the centre of the nth interval, i.e. at a time $(n - \frac{1}{2})\Delta t$. In order to produce a generalised solution, a large number of temperature-time series has been evaluated, using the basic assumptions given previously. It is worth noting however, that in any particular situation, the solutions may be obtained if all the assumptions except (e) are discarded, so long as the variation of all the relevant terms is known as a function of temperature or of time.

Typical solutions have been worked out in the range 0.01 < b < 1.0, within which most practical situations are believed to lie. Some of these are shown in Fig.3, the working having been concluded just after the maxima had been reached. For these solutions, the time intervals used were $\Delta t/t_{max} = 0.25$.

In Figs.4 and 5, the maximum non-dimensional temperature rise T_m/T_i and the non-dimensional time t_m/t_{max} at which it occurs are plotted against

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the parameter b. A difficulty was encountered in determining these values when they occurred after 10 t_{max}, since there are no input data beyond this point, which corresponds approximately to b = 0.01. In Fig.4, the extrapolation down to b = 0.005 has been dotted to emphasise its hypothetical nature. This extrapolation is made since situations involving low-yield weapons and little cooling have been found to involve values of b somewhat below 0.01.

5   DISCUSSION

It may be seen from Fig.4 that the maximum temperature rise in an aircraft skin in the presence of aerodynamic cooling is substantially less than has been assumed hitherto when no allowance for cooling has been made. The variation of maximum temperature rise with the parameter b is not rapid over the range 0.01 < b < 0.1, which is believed to be the most important range. It therefore appears that the values of the properties which compose b need not be known with extreme accuracy in order to determine the maximum temperature rise with some confidence.

In using Fig.4, it must be remembered that although high values of h and t_{max} invariably favour low temperature rises, small values of $(zc\ell)$ not only increase the value of b, but also that of T_i, since

$$T_i = \frac{Q}{zc\ell} \qquad (10)$$

Thus, thin skins always suffer greater temperature rises than thicker ones, even though they favour lower values of T_m/T_i. This is illustrated in Fig.6, for example, where the actual maximum temperature rise is plotted against $h\,t_{max}$ for skins of various thicknesses in DTD.546 material. Fig.6 also demonstrates more clearly than does Fig.4 the relative insensitivity of the maximum temperature rise to the heat transfer coefficient. Even in the thinnest material, a change in h by a factor of two changes T_m by about 10-20%.

When the skin is very thin, the reflective paint applied to the surfaces may contribute significantly to the heat capacity. If the same assumptions are made as in Section 4, the subsequent analysis is applicable when the product $(zc\ell)$ is replaced by the total heat capacity per unit area of the skin together with its paint.

It is important to note that, when aerodynamic cooling is taken into account, it is no longer possible to state a maximum thermal dose which a given aircraft will withstand, when this is limited by the rise in skin temperature. Any such critical dose must be associated with the yield of the weapon from which it emanates. In general, a greater total thermal dose may be accepted from a weapon with a high yield than from one with a low yield, because of the increase in the time scale for the former weapon.

6   ILLUSTRATIVE EXAMPLE

An example involving a hypothetical situation is worked out below as an illustration of the use of the results.

The maximum temperature rise in the aileron skin of a bomber is required when a total thermal dose, corrected for reflectivity and obliquity

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of the surface, of 10 cals cm^{-2} is received from a 2 Mt. explosion. The skin is 26 gauge light alloy to DTD 546 and the point of interest is 12 ft downstream from the leading edge. The aircraft is flying straight and level at $M = 0.8$ at 45,000 ft.

It will be assumed, in this example, that the temperature rise is small enough for the properties of the air to be evaluated at ambient conditions, i.e.,

$$\rho = 4.6 \times 10^{-4} \text{ slugs} \times ft^{-3}$$

$$\mu = 2.94 \times 10^{-8} \text{ slugs} \times ft^{-1} sec^{-1}$$

$$x = 12 \text{ ft}$$

$$V = 795 \text{ ft sec}^{-1}$$

Then $Re = \dfrac{\rho V x}{\mu} = 1.49 \times 10^{7}$. The boundary layer would thus be turbulent, and from equation (5).

$$h = 0.176 \times \rho V Cp \ (log_{10} Re)^{-2.45}$$

$$h = 3.29 \times 10^{-3} \text{ CHU ft}^{-2} sec^{-1} \ ^oC^{-1}$$

$$= 1.61 \times 10^{-3} \text{ cals cm}^{-2} sec^{-1} \ ^oC^{-1}$$

From equation (3)

$$t_{max} = 0.032 \ W^{\frac{1}{2}} \text{ secs}$$

$$= 1.43 \text{ secs.}$$

For 26 gauge DTD.546

$$(zc\ell) = 0.0262 \text{ cals cm}^{-2} \ ^oC^{-1}.$$

Then from equation (11)

$$b = \frac{h \, t_{max}}{zc\ell}$$

$$= 0.088$$

From Fig.4

$$T_m/T_i = 0.56$$

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From equation (10)

$$T_i = Q/zo\ell$$

$$= 381°C$$

Then

$$T_m = 213°C .$$

From Fig.5

$$t_m/t_{max} = 3.75 .$$

Then

$$t_m = 5.36 \text{ secs.}$$

Thus, the maximum temperature rise is 213°C occurring 5.36 secs after burst.

7   CONCLUSIONS

A simplified analysis has been made of the effects of aerodynamic cooling on the temperature rise of thin skins exposed to thermal radiation from nuclear weapons.

It is shown that the maximum temperature rise, expressed as a fraction of the value which would result without cooling, is a function of a single non-dimensional parameter.   A curve is given of this function together with a curve showing the time at which the maximum temperature rise occurs, also in non-dimensional form.

The results indicate that the maximum temperature rise is substantially reduced by aerodynamic cooling in many practical situations. Attention is drawn to the fact that the maximum thermal dose which a structure may withstand depends upon the yield of the weapon from which it emanates.

————

NOTATION

The symbols used are defined as follows:

b   parameter $\dfrac{h\,t_{max}}{zc\ell}$

c   specific heat of skin material

Cp   specific heat of air at constant pressure

h   heat transfer coefficient

k   thermal conductivity of air

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ℓ skin thickness

t time after burst

t_{max} time at which $P(t) = P_{max}$

t_m time at which $T = T_m$

Δt interval of time

x distance of point from leading edge

z density of skin material

Pr Prandtl number $\dfrac{Cp\,\mu}{k}$

$P(t)$ rate of emission or reception of thermal energy at time t

P_{max} maximum value of $P(t)$

$Q(t)$ thermal energy emitted or received up to time t

$\Delta Q(t)$ increment of $Q(t)$ in time interval Δt

Q total thermal energy emitted or received

Re_x Reynolds number $\dfrac{\rho\,V\,x}{\mu}$

T temperature rise

T_i "ideal" temperature rise $\dfrac{Q}{zc\ell}$

T_m maximum temperature rise

T_n temperature rise at centre of nth time interval

ΔT_n temperature rise during nth interval

$\overline{T_n}$ temperature rise at end of nth interval

W weapon yield in kilotons

ρ density of air

μ viscosity of air

LIST OF REFERENCES

Ref. No.	Author	Title, etc.
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2		AWRE communication.
3	R. J. Monaghan	Formulae and approximations for aerodynamic heating rates in high speed flight. R.A.E. Tech. Note No. Aero 2407. 1955.
4	R. J. Monaghan	On the behaviour of boundary layers at supersonic speeds. 5th Int. Aero. Conf. 1955.
5	R. J. Monaghan	A survey and correlation of data on heat transfer by forced convection at supersonic speeds. R.A.E. Tech. Note No. Aero 2259. 1953.
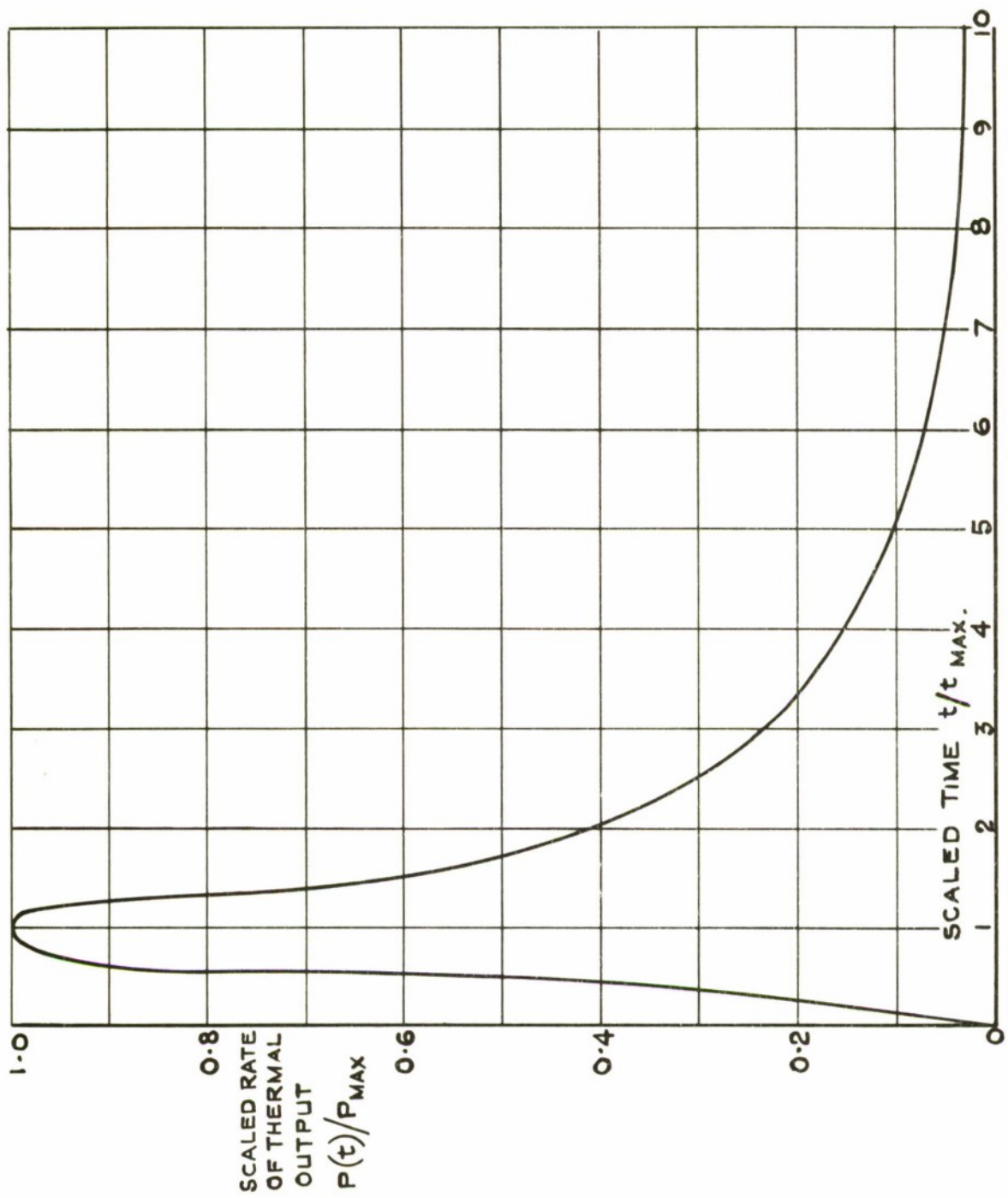
Fig. 1--Shape of generalised thermal pulse.

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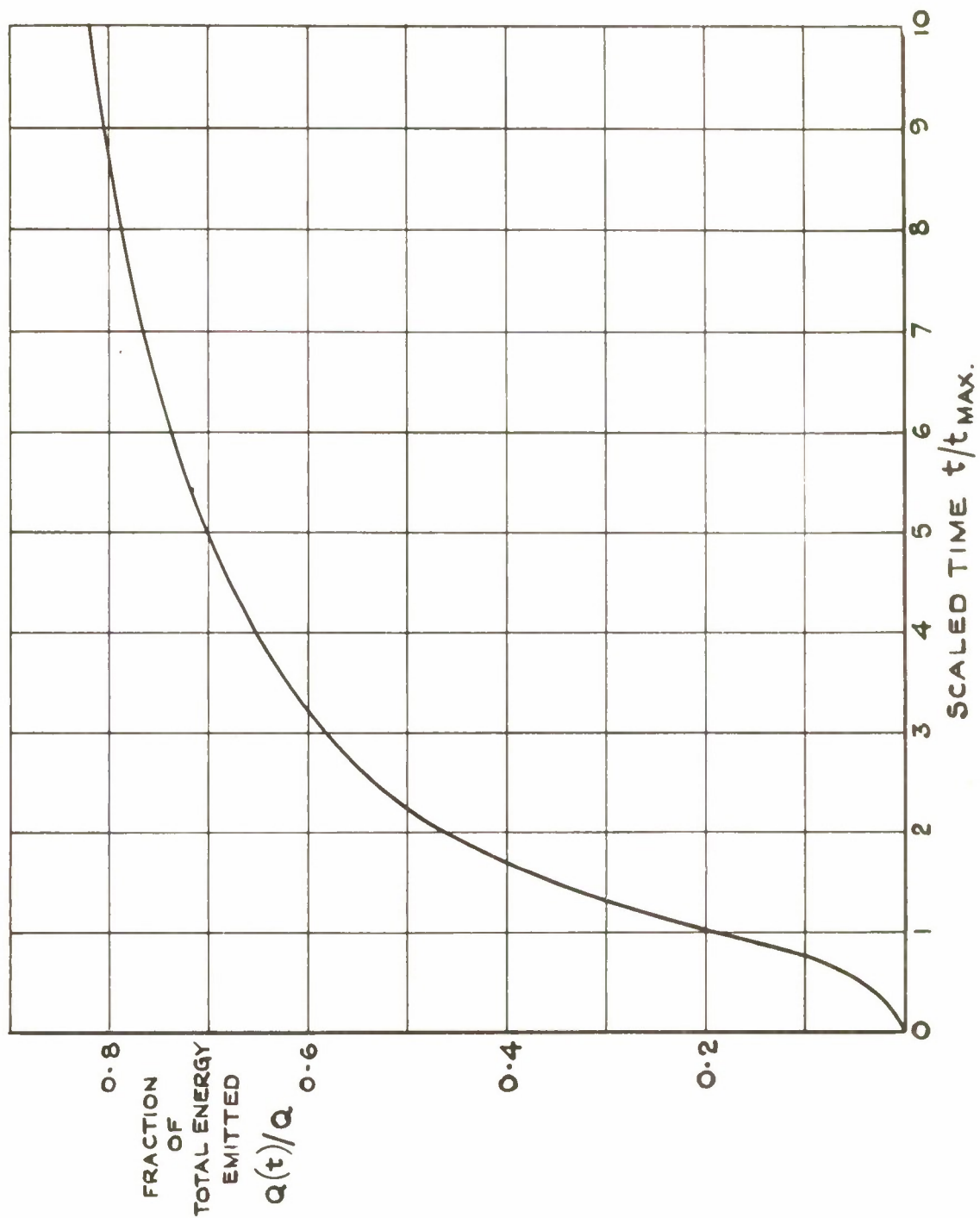
Fig. 2--Fraction of total energy emitted or received.
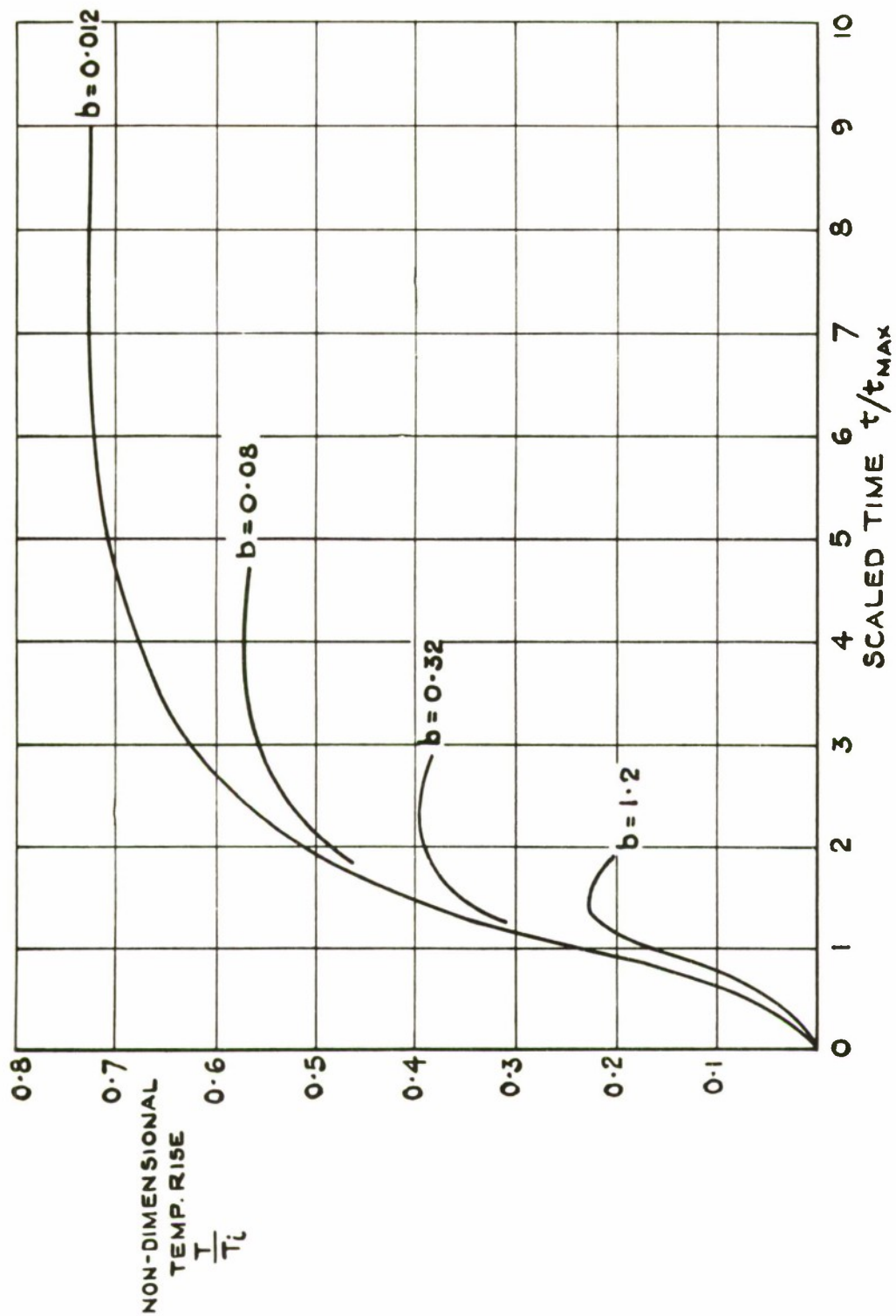
Fig. 3—Time-history of temperature rise.

MAX.
NON-DIMENSIONAL
TEMP RISE
$\dfrac{T_m}{T_i}$

$b = \dfrac{k \, t_{MAX}}{z \, c \, \ell}$
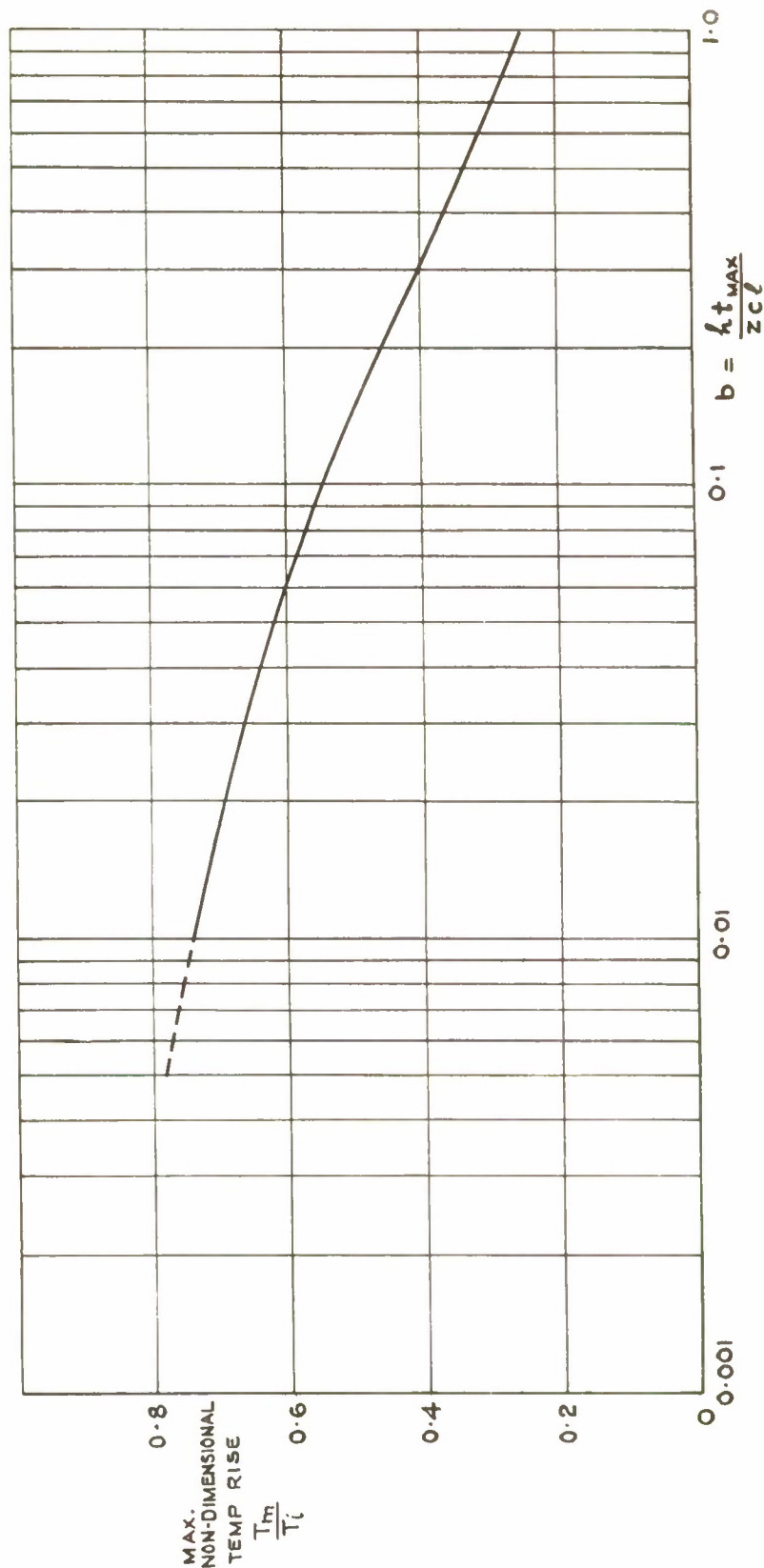
Fig. 4.—Maximum temperature rise.
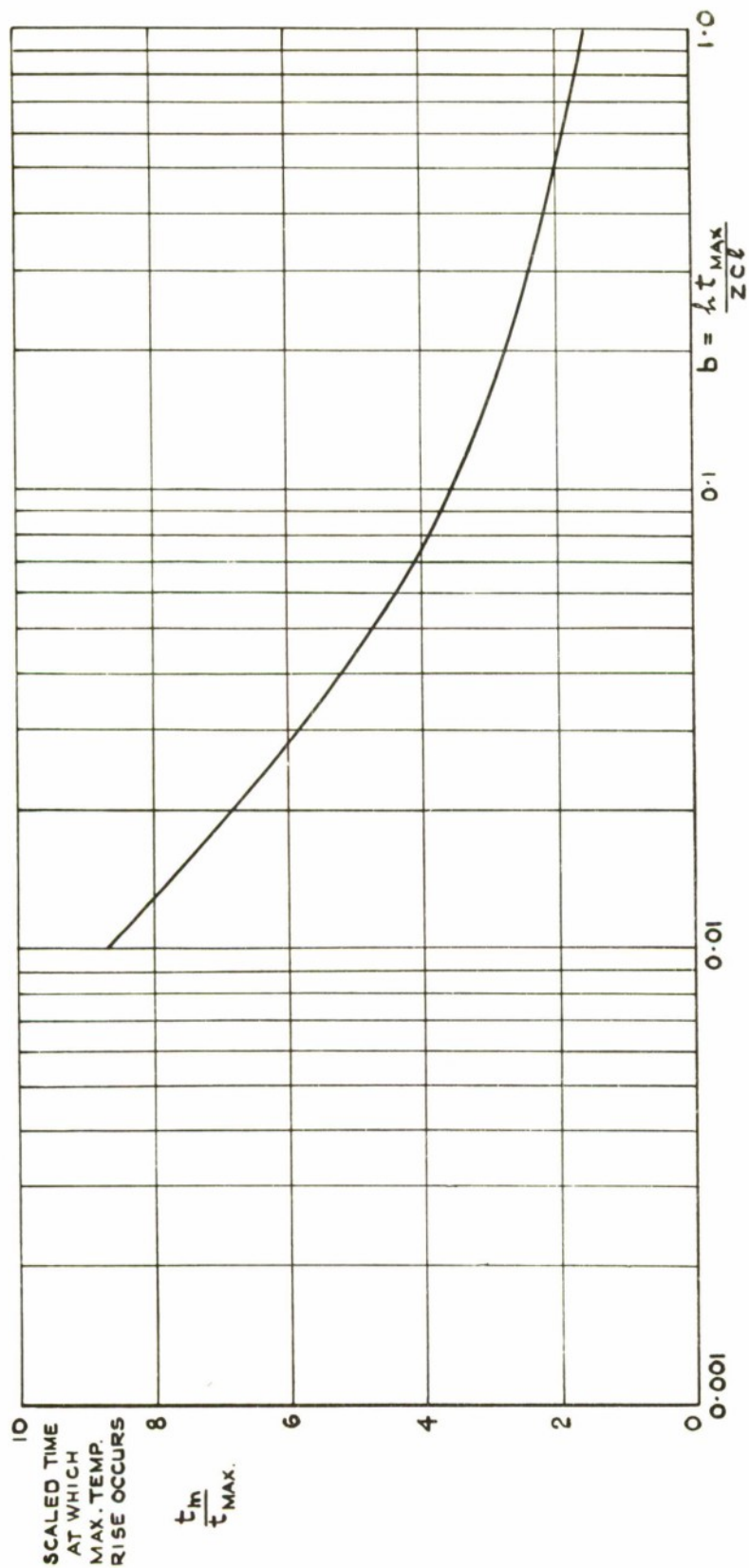
Fig. 5.—Time to maximum temperature rise.

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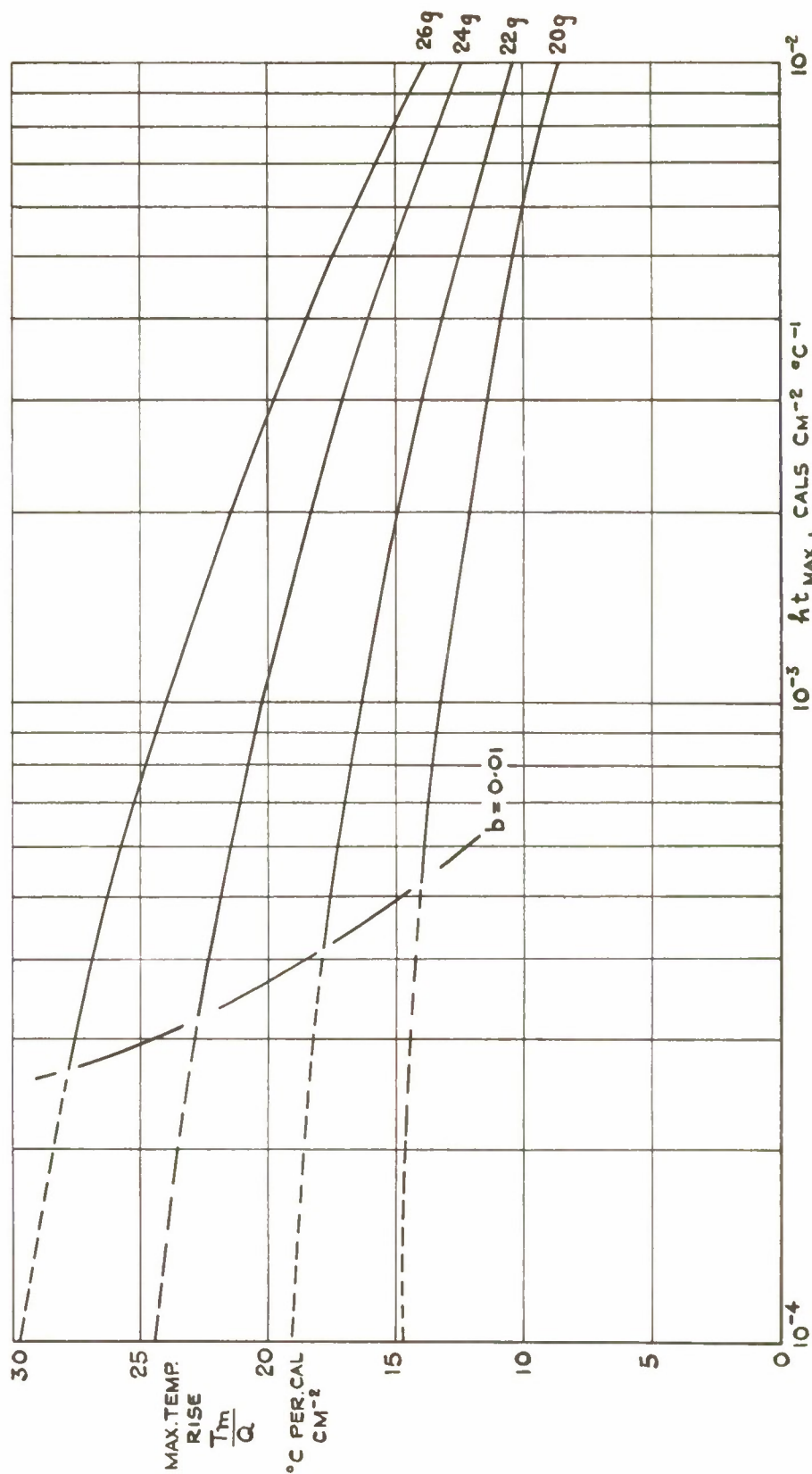
Fig. 6—Maximum temperature rise in DTD 546 skin.

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